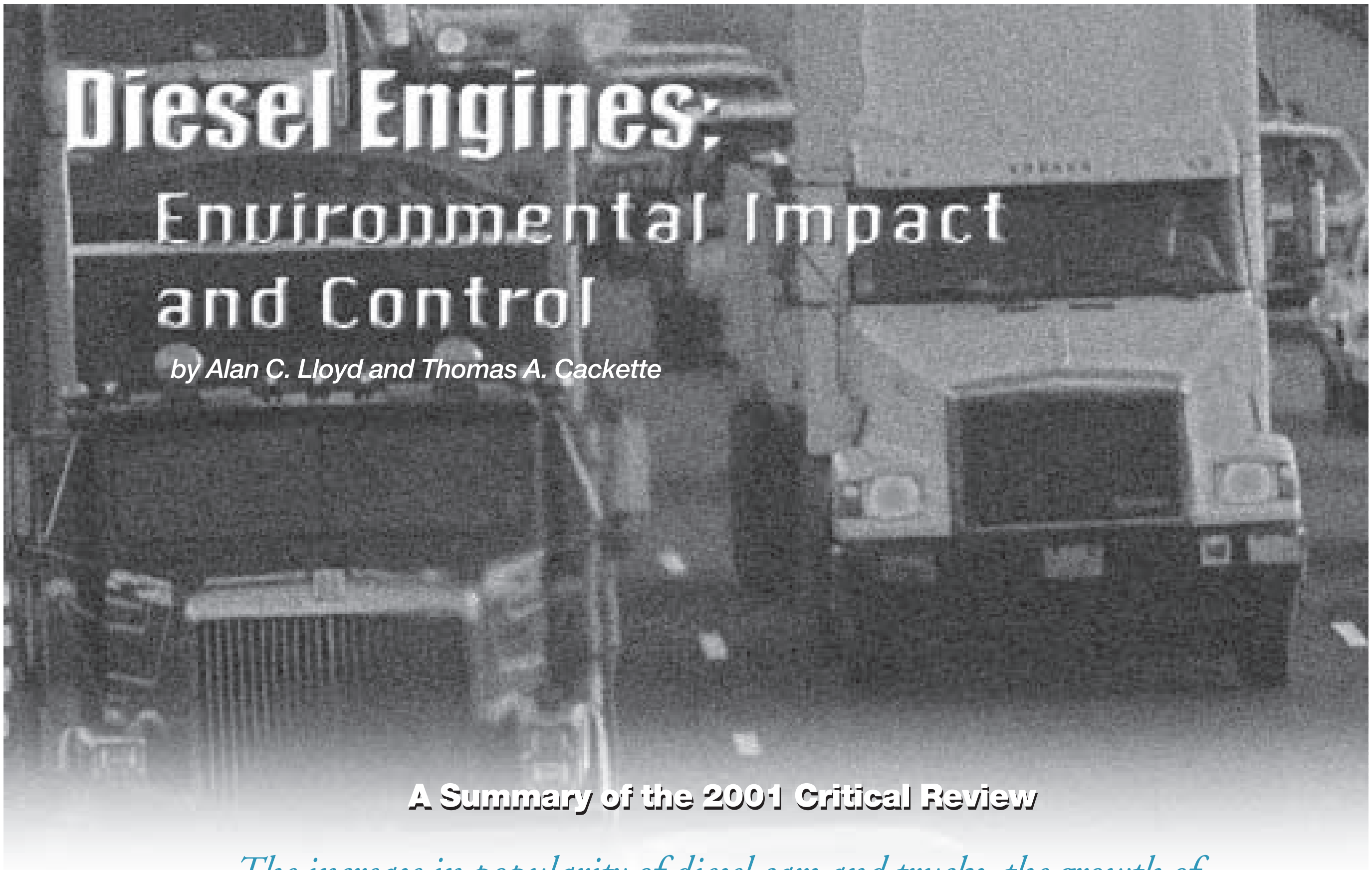

Diesel Engines: Environmental Impact and Control

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A Summary of the 2001 Critical Review

The increase in popularity of diesel cars and trucks, the growth of the diesel engine as an alternative power source, and the increase of diesel fuel consumption worldwide are at odds with the growing concern that diesel pollution may inflict serious damage on the natural environment and human health. The economical diesel engine may be more costly than we think.

INTRODUCTION

The evolution of reliable ways to power our farm, construction, and industrial equipment, as well as transport our commercial products to the consumer, has been a cornerstone in the development of modern society (see Figure 1). The diesel engine plays a vital role in this process, powering much of our land and sea transportation, generating electrical power, and fueling many of the vehicles and equipment that support agriculture and industry. It accomplishes this in a rugged, dependable package that is fuel-efficient and costs significantly less to operate than a comparable gasoline engine. But diesel operation comes with a price: it pollutes. And concern is growing over how much diesel pollution is impacting public health and the environment. Technological advances, in combination with effective regulatory actions, offer the most effective way to reduce these impacts without sacrificing the benefits of diesel.

EXISTING DIESEL TECHNOLOGY

Much of the history of the modern internal combustion engine has involved a search for the best way to get more power for less fuel cost. In its present refined form, the diesel engine does indeed provide more power at a lower cost, using only about 70% of the fuel that a comparable gasoline engine consumes for the same power output at full load and significantly less under partial load conditions.[1,2] This has made it the most attractive choice for vehicular and mechanical power, particularly for the transportation of goods. This is especially important, since the transport of goods is a major underpinning of our modern economy. There are, however, some drawbacks associated with the diesel engine. Its rugged durability makes it heavier and more costly to purchase than a gasoline engine of comparable output. It also produces less power per unit displacement than a gasoline engine, since its lean combustion burns less fuel per unit displacement. The diesel's diffusion flame combustion process is also slower than the premixed combustion of the typical gasoline engine, which has generally limited diesel engines to lower maximum operating speeds.[1] And finally, there is one major drawback to the diesel engine: pollution.

Figure 1. The diesel vehicle is a common sight on our streets and highways, transporting goods and people as a vital part of our economies.

DIESEL AND THE ENVIRONMENT

Diesel engines and their fueling infrastructure adversely affect all aspects of the natural environment—land, water, and air. Diesel exhaust consists of hundreds of gas-phase, particle-phase, and semi-volatile organic compounds, including typical combustion products, such as carbon dioxide (CO_2), hydrogen, oxygen, and water vapor, as well as carbon monoxide (CO), volatile organic compounds (VOCs), carbonyls, alkenes, aromatic hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), PAH derivatives, and oxides of sulfur (SO_x)—compounds resulting from incomplete combustion.[3-5] The hydrocarbon (HC) and nitrogen oxides (NO_x) emissions from diesel combustion contribute to smog formation, and the particulate matter (PM) emissions impair visibility. Results from studies of intense urban hazes, known as "brown clouds," in the Phoenix, AZ,[6] and Denver, CO,[7] metropolitan areas, as well as other studies in California[8-10] and Vienna, Austria,[11,12] have determined that, although diesels constitute only about 5% of road vehicles, they contribute anywhere from one-tenth to three-quarters of the optically active PM in urban areas, depending on surrounding source characteristics. In addition, the deposition of airborne diesel particles on the surfaces of buildings, tunnels, highway bridges, and culturally important articles (e.g., statues) can cause damage and soiling, thus reducing the useful life and aesthetic appeal of such structures.

There are also impacts associated with the production of diesel engines and vehicles, and the production, storage, and distribution of diesel fuel. Environmental impacts are often quite visible, although the full extent of the damage may not appear immediately following exposure. For example, pollutants (largely HCs) are released from wells, refineries, storage tanks, and pipelines, either into the atmosphere or by leakage into the ground and groundwater. Runoff carries part of this pollution to surface water, while the various deposition processes add airborne pollutants to the ground and surface water burdens.[13,14] Many of the chemicals, such as heavy metals and PAHs, are long-lived in the environment.[15,16] Because of their sufficiently high molecular weight and high lipid solubility, these compounds do not readily evaporate and tend to accumulate in sediments if released into aquatic environments. This can pose a chronic threat to aquatic organisms long after the acute initial effects of the spill have abated, including mortality, reproductive impairment, depressed growth rates, and increased susceptibility to infectious and non-infectious diseases.[17-22] The long-term impacts caused by the leakage of tanks and pipelines can be even more significant than the immediately visible fuel spills. Because the leakage usually occurs over a long period of time before it is noticed, and usually does not impose a widespread, immediate threat to human health or the natural world, it does not garner the publicity and attention accorded major spills. It can, however, damage fish and wildlife, increase levels of toxic compounds, and contaminate sediments and, possibly, groundwater.[23-25] Cleanup can also be very costly.

Environmental damage from diesel impacts is not restricted to the perimeters of individual events or well-defined state or local environs. Pollutants easily cross political boundaries, and regional and global circulation patterns often make even natural barriers irrelevant. The diesel engine's higher efficiency means it emits less CO_2 than equivalent gasoline-fueled engines. Because CO_2 is the principal greenhouse gas, concerns about global warming have made diesel engines appear to be an attractive alternative to gasoline power. However, the potential global warming benefits of diesel vehicles have been undercut by recent studies, which indicate that diesel particles may alter cloud cover and rainfall, possibly offsetting any CO_2 advantage.[26]

It is clearly evident that the environmental impacts of diesel usage are strongly multimedia in nature, requiring the active involvement of ground and water protection interests, as well as the air quality community, to address its consequences.

DIESEL AND HEALTH

Although diesel exhaust emissions contribute a small fraction of the organic compounds released to the atmosphere, their health impacts are significant. Some of the components of HC emissions and, most recently, PM emissions have been identified as toxic substances, with the potential for serious adverse health effects.[27,28] PAHs and dioxins, the most toxic compounds resulting from petroleum hydrocarbon combustion, are abundant in diesel exhaust and exhibit a wide range of physicochemical properties that influence their environmental fate.[29,30] Heavy metals, PAHs, and dioxins can be transported long distances as gases or aerosols, and are apparently resistant to degradation on atmospheric particles. As a result, heavy metals, PAHs, and dioxins are found in relatively high concentrations in many rural and remote areas.[29,30]

The most potentially significant health effect of diesel exhaust exposure is its apparent ability to act as an adjuvant in allergic responses and possibly asthma.[31-33] However, additional research is needed at diesel exhaust concentrations that more closely approximate current ambient levels before the role of diesel exhaust exposure in the increasing allergy and asthma rates in the United States and industrialized world is established.

Diesel PM (DPM) has also been linked with lung cancer. More than 30 human epidemiological studies have investigated the potential carcinogenicity of diesel exhaust. On average, these studies found that long-term occupational exposures to diesel exhaust were associated with a 40% increase in the relative risk of lung cancer.[34] Several organizations have reviewed the epidemiology and experimental studies associated with diesel exhaust and lung cancer and have reached similar conclusions (see Table 1). The carcinogenic potential of diesel exhaust has also been demonstrated in numerous genotoxic and mutagenic studies on some of the organic compounds typically detected in diesel exhaust.[34] The damage to DNA could, for example, take the form of changes in DNA base sequences (mutations) or gross structural changes to chromosomes. There is limited diesel-specific information that addresses variable susceptibility to carcinogenicity within the general human population and vulnerable subgroups, including infants and children and people with pre-existing health conditions. More research is needed to identify risk factors specific to these groups.

EXISTING DIESEL CONTROLS

Diesel engines emit relatively high levels of NO_x and DPM, compared to the well-controlled gasoline engines used in most motor vehicles. Current controls encompass regulatory standards, the application of emission control technology, and improved quality control for diesel fuel, with an emphasis on reduced sulfur content. Since regulatory standards were first introduced in the 1970s, there has been a continuous trend toward cleaner engines in both Europe and the United States.[35-37] Current emissions are, on average, more than 75% lower than pre-controlled levels. Significant progress has been made in reducing diesel emissions through improved engine design and fuel reformulation. These advances have often improved fuel economy, thereby offsetting some of the costs of new technology. Since 1980, up to 90% reductions in DPM and NO_x emissions have been achieved with fuel injection rate shaping and combustion system refinements. However, current controls involve trade-offs between DPM and NO_x emissions and may result in decreased fuel economy. Some strategies currently used to control both diesel NO_x and DPM emissions include turbocharging, aftercooling, combustion chamber design changes, injection timing retard, and high-pressure fuel injection.[38-41]

It is expected that high-efficiency aftertreatment devices will effectively reduce emissions even further, but these devices require fuels with sulfur contents <15 parts per million by weight (ppmw),

Table 1. Summary of cancer health effects evaluations conducted by several organizations.

Organization	Human Data	Animal Data	Overall Evaluation
NIOSH (1988)	Limited	Confirmatory	Potential occupational carcinogen
IARC (1989)	Limited	Sufficient	Probably carcinogenic to humans
IPCS (1996)	N/A	N/A	Probably carcinogenic to humans
California Proposition 65 (1990)	Based on IARC findings	Based on IARC findings	Substance "known to the state to cause cancer"
California EPA (1998)	"Consistent evidence for a causal association"	"Demonstrated carcinogenicity"	Diesel exhaust particulate as a "toxic air contaminant"
U.S. EPA (2000)	"Strong but less than sufficient evidence for a causal association"	"Sufficient animal evidence for the induction of lung cancer in the rat"	Diesel exhaust is a "probable human carcinogen" and "likely to be carcinogenic to humans" at environmental levels
U.S. DHHS (2000)	"Elevated lung cancer in occupationally exposed groups"	"Supporting animal and mechanistic data"	Reasonably anticipated to be a carcinogen

possibly as low as 5 ppmw. Reducing the sulfur content of diesel fuels contributes directly to the reduction of SO_x and DPM emissions and indirectly to the reduction in emissions of NO_x, CO, and HCs. Emissions of fine DPM and benzene are especially sensitive to fuel sulfur content and lower fuel aromatic content reduces NO_x emissions. Fuel sulfur content can affect engine wear, deposit formation, and emission performance. Fuel sulfur that is not deposited within the fuel system, engine, or exhaust system is emitted as sulfurous compounds, such as gaseous sulfur dioxide (SO_2) and particulate sulfates (SO_4^{-2}). Sulfur compounds in engine exhaust can also reduce the effectiveness of emission control equipment. With the implementation of diesel fuel standards in the 1990s, improvements in diesel fuel quality have brought significant reductions in SO_2 and DPM emissions from diesel engines. In California and some countries around the world, other emissions have been reduced as well.[42]

Reformulated and alternative diesel fuels have also shown promise for achieving significant reductions in DPM and NO_x emissions. In addition to very low sulfur contents, all of these fuels are relatively low density, with relatively low aromatic and PAH contents. Synthetic diesel fuel, with nearly zero sulfur and aromatic contents, is the cleanest burning of the reformulated diesel fuels. Other reformulated and alternative diesel fuels, such as ARCO's Emission Control-Diesel (EC-D), Lubrizol's PuriNO_x, and biodiesel (a mono alkyl ester-based oxygenated fuel made from vegetable oil or animal fats), also demonstrated emission reductions of PM, NO_x, HC, and/or CO, over standard diesel fuels.

ALTERNATIVES TO DIESEL

Outside the United States, diesel engines represent a much higher proportion of the in-use vehicle fleet, particularly for light-duty vehicles. In the United States, increased diesel penetration has been proposed as one way to reduce CO_2 emissions and associated global climate change impacts from the transportation sector. However, DPM also negatively affects the global radiation balance, and a better understanding is needed of the comparative impacts of diesel, gasoline, and alternative fuels. The U.S. Department of Energy (DOE) recognizes substantially nonpetroleum fuels with energy security and environmental benefits as alternative fuels. Among others, DOE lists methanol, natural gas (both compressed and liquefied), and hydrogen as alternative fuels.[43]

In the heavy-duty arena, where diesels are the dominant technology, there has been interest in other fuel and technology types. Many newer urban transit buses now use compressed natural gas (CNG), and a limited fueling network for liquefied natural gas (LNG) is being developed to support intrastate trucks. However, results of recent studies[44,45] (and work yet to be published) seem to indicate that, while natural gas-fueled engines have the capacity for greatly reduced emissions, relative to diesel engines, this cleanliness does not come automatically and requires careful engineering and, perhaps, maintenance to achieve. Additionally, although PM mass emissions of natural gas engines are generally lower than those of diesel engines, there is an awareness that these emissions are different in character, composition, size, and, potentially, their effects on human health. Despite the lack of a widespread fueling infrastructure, both liquefied petroleum gas (LPG) and CNG have shown a steady growth in usage since 1992.[46,47] LPG is also frequently used in stationary engines for applications that might otherwise make use of diesel engines. Recent California certification of stationary engines using LPG show low levels of PM and NO_x emissions relative to the certification standards.

Although methanol is listed by DOE as an alternative fuel, the large methanol-fueled fleets of the 1990s no longer exist,[48] due primarily to durability issues and the need for excessively frequent overhauls.[49] Additionally, no major U.S. heavy-duty engine manufacturer currently produces methanol-fueled engines as an alternative to its diesel-fueled product line. In fact, there were only about 200 heavy-duty methanol-fueled (straight methanol or M100) vehicles estimated in use in the United States in 2000.[46] Methanol may, however, prove to be a viable fuel for use with future fuel cell-powered vehicles.

Di-methyl ether (DME) is not explicitly included on DOE's list of alternative fuels (see *http://www.afdc.doe.gov/questions.html*), perhaps because work with it is relatively new and its use is not widespread. However, testing does show the potential for emission benefits.[50] Its high cetane rating (nearly 60, compared to diesel fuel ratings in the low to mid-50s) means that it can be readily used in the diesel compression ignition cycle and infers that high thermal efficiencies (and thus good fuel economies), comparable to the conventionally-fueled diesel engine, can be expected.[50] It is anticipated that the use of Fischer-Tropsch and DME will increase as the technologies to remotely manufacture these fuels become cost competitive and the infrastructure to support these fuels improves.

Another promising heavy-duty technology being demonstrated is the hybrid-electric engine system. Manufacturers of such hybrid system technology are currently focusing on the transit bus market, but the technology could also provide benefits in numerous other heavy-duty applications.

Fuel cells that convert hydrogen and oxygen to energy and water should begin to replace or complement diesel engines within this decade. Hydrogen can be economically generated from renewable sources, such as wind, solar, or geothermal; it can also be produced by reforming currently available hydrocarbon fuels, such as gasoline, diesel, Fischer-Tropsch, natural gas, methanol, and ethanol. Fuel cell engines are currently practical for city buses that have a central fueling facility where hydrogen can be provided. Argonne National Laboratory calculations with the Greenhouse Gases Regulated Emission and Energy Use in Transportation (GREET) model predict a reduced total energy consumption, fossil energy consumption, greenhouse gas emissions, VOCs, and CO for fuel cell vehicles, compared to internal combustion engine vehicles.[51] The California Air Resources Board (CARB) has encouraged adoption of fuel cell technology with the implementation of the 2001 Transit Bus Regulations, requiring large transit bus fleets that are predominantly diesel-fueled to demonstrate zero-emission buses, starting in July 2003.[52] Fuel cells are one of the three alternative technologies that qualify. Fuel cell auxiliary power units with 1 to 5 kilowatt capacity have been shown to reduce emissions and improve fuel economy, when used instead of diesel engines in long-haul trucks while parked. Fuel cell costs are expected to drop as manufacturing methods and sales volumes improve.

TECHNOLOGIES AND CONTROLS FOR THE FUTURE

The next generation of in-use compliance programs will expand the current program for heavy-duty vehicles by adding testing for excessive NO_x and PM emissions to the existing smoke inspection programs. California, the U.S. Environmental Protection Agency (EPA), and some foreign countries are conducting studies to develop dynamometer-based emissions inspections for heavy-duty, diesel-powered vehicles. Emission inspections in the future will focus on in-use compliance testing, designed to identify emissions defects resulting from both owner malmaintenance/tampering and poorly designed or low durability emissions control systems (see Figure 2).[53]

Figure 2. Poorly maintained, tampered, or worn-out emission control equipment and engines can be detected and subsequently corrected through inspection and testing programs. Significant air quality benefits can result.

In the United States, beginning June 1, 2006, refiners must begin producing highway diesel fuel that meets a maximum sulfur standard of 15 ppmw. All 2007 and later model-year diesel-fueled vehicles must operate with this new low sulfur diesel fuel.[54] California's Risk Reduction Plan calls for the adoption of a maximum sulfur standard of 15 ppmw for diesel fuel. This standard would also be effective June 1, 2006. As planned, the CARB diesel applicability will be extended to stationary and other diesel engines with the adoption of airborne toxicant control measures for nonvehicular sources. European Union countries will limit sulfur in diesel fuel to 50 ppmw by 2005. Other European countries, as well as Australia and some Asian countries, are also moving forward toward lower sulfur standards (see Table 2).

To meet the near-term on- and off-road exhaust emission standards, improvements to the existing emission control strategies are expected, rather than the application of aftertreatment devices. It is also expected that additional engine strategies will be needed, including fuel-injection rate shaping, exhaust gas recirculation (EGR), and advanced combustion techniques.[55] However, as combustion system refinements and EGR reach the limit of their emission reduction capabilities, NO_x and PM aftertreatment devices will be needed to comply with increasingly stringent emission standards, such as the 2007 on-road standards. Sulfur levels in off-road diesel fuel will need to be similarly reduced in order to allow the transfer of on-road emission control technology to off-road engines. NO_x aftertreatment devices under development for 2007 include the lean NO_x catalyst, the NO_x adsorber, and selective catalytic reduction (SCR). Lean NO_x catalysts (active systems with diesel fuel as the reductant) have been shown to provide NO_x reductions of up to 30% under certain operating conditions, although a 7% increase in fuel consumption, for supplying the reductant, results.[56-58]

California's Diesel Risk Reduction Plan intends to reduce public exposure to diesel exhaust PM by retrofitting both on- and off-road diesel engines with high-efficiency diesel particulate filters (DPFs).[59] Worldwide, more than 10,000 buses and trucks have already been equipped with passive high-efficiency DPFs, with some vehicles accumulating more than 300,000 miles.[60] One study showed that continuously-regenerating DPFs reduced the PM number count by 1 to 2 orders of magnitude, as well as substantially reducing mass emissions.[61] Development and demonstration of DPF systems for on- and off-road sources are underway in many countries, including Sweden (Clean Cities Program), Switzerland, Germany, Great Britain, Finland, France, South Korea, Taiwan, and the United States.[62-66]

RECOMMENDATIONS AND CONCLUSIONS

Environmental regulations are needed to stimulate further progress in reducing diesel and other vehicle emissions. Most of the technological advances that are appreciated today would not exist if the diesel industry had not been challenged by more stringent emissions standards. Regulations should be based on good science that is practical to implement, inclusive of public and industry concerns, and on a reasonable time schedule. Currently promulgated regulations for on-road vehicles should provide considerable improvements to air quality on urban, regional, and global scales. These regulations, which will require the use of exhaust aftertreatment, need to be extended to off-road diesel applications. This can only happen if ultra-low

Table 2. Summary of diesel fuel regulations and incentive programs for selected countries.

Country	Regulation or Incentive	Max S limit	Conventional Fuel Limit (and Typical Content)	Date Introduced
EU	EURO2		500 ppmw (450)	Jan 1997
	98/70/EC EURO3		350 ppmw	Jan 2000
	98/70/EC EURO4		50 ppmw	Jan 2005
Belgium	National incentive	50 ppmw	350 ppmw	Oct 2001
Denmark[1]	National incentive	50 ppmw	500 ppmw	June 1999
Finland[2]	National incentive	50 ppmw	350 ppmw	2002
	Neste/Fortum Initiative	10 ppmw		
Germany[3]	National incentive	50 ppmw	350 ppmw	Nov 2001
		10 ppmw		Jan 2003
Netherlands	National incentive	50 ppmw	350 ppmw	Jan 2001
Sweden	National incentive[4]	10 ppmw	2000 ppmw	1991
	National incentive[5]	10 ppmw	350 ppmw	2001
		50 ppmw	350 ppmw	2001
Switzerland	National incentive	50/10 ppmw[6]	350 ppmw	2003
	Agrola initiative	10 ppmw[7]	350 ppmw	2000
	BP initiative	10 ppmw[8]	350 ppmw	2000
UK	National incentive	50 ppmw	500 ppmw	March 1999
	National incentive	50 ppmw	350 ppmw	March 2001
Australia	National regulation	50 ppmw	1300 ppmw	Jan 2006
	BP initiative[9]	50 ppmw	500 ppmw	End 2000
Hong Kong[10]	"Ultra low sulphur" national incentive	50 ppmw	500 ppmw	July 2000
Japan[11]	National regulatory proposal	50 ppmw	500 ppmw	Before 2005

[1]100% penetration by July 1999 (selected from Report to Committee of Deputies, European Conference of Ministers of Transport, March 2001); [2]100% penetration; [3]from 2003, the incentive will shift from 50 ppmw fuels to 10 ppmw fuels; [4]city diesel; [5]current incentive, last adjusted January 2001; [6]proposal before parliament; [7]small market share; [8]supply to public transport and army; [9]capacity to supply 12% of national market; [10]replaced regular diesel at all filling stations, but high sulfur fuel still used by bus fleets as tax free; [11]Japan Air Quality Committee has recommended further reduction in the future.

sulfur diesel fuel is available for off-road engines, as it will be for on-road engines beginning in 2006.

Additional monitoring of on-road emission performance is needed. Diesel certification tests are insufficient to understand how emissions change with variable driving conditions. They do not identify engines that are operating outside their range of specification. On-board and remote sensing systems exist to take these measurements, and these need to be incorporated into a comprehensive program to monitor actual emissions and enforce emissions standards for individual vehicles.

Programs that introduce zero-emission technologies, such as fuel cell engines, as replacements for diesels need to be continued and enhanced. The cost-effectiveness of mass production, hydrogen production, and fuel distribution will not be realized until a critical mass of such vehicles exists. Practical problems with vehicle operation and maintenance will be identified and solved by these programs. This will increase public acceptance of hydrogen and other fuels that are perceived to be, but actually are not, more dangerous than the gasoline and diesel fuels in current use.

Better methods and data are needed to quantify the environmental trade-offs among diesel, gasoline, alternative fuels, and possible control technologies. This information will help ensure that decisions on future fuel strategies, fuel infrastructure investment, and regulation result in more environmentally benign modes of transport and power generation and protection for the health of future generations.

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ABOUT THE CRITICAL REVIEW

The Critical Review program was established by A&WMA (then the Air Pollution Control Association) in 1973 to stimulate discussion of major issues of concern in air pollution control. As the Association grew, the scope of the Critical Review expanded to include waste management and other environmental media. Dr. Alan Lloyd, chairman of the California AIr Resources Board, will present the first Critical Review of the new millenium in its entirety at the 94th Annual Conference & Exhibition in Orlando, FL, on Wednesday, June 27, starting at 8:00 a.m. The complete 2001 Critical Review will also be published in the June issue of the *Journal of the Air and Waste Management Association.*

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